ABSTRACTS

River Protection Program Characterization Needs

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The River Protection Program consists of those contractors who perform work associated with the wastes stored in the large underground tanks at Hanford. CH2M Hill Hanford Group (CHG) is now responsible for managing the tank farms, for retrieving the waste from the tanks and delivering it to BNFL, Inc, and for storing and disposing of the treated (immobilized) waste. Two CHG activities (the Tank Farm Vadose Zone Program and the Immobilized Low-Activity Waste [Performance Assessment [ILAW PA] activity of the Immobilized Waste Program) are and will be performing field characterizations to support this effort. This paper briefly describes the goals, the background, the tasks, and the characterization needs and plans for the activities. Throughout the workshop, members of the CHG organizations will be available to answer questions.

Overview of Vadose Zone Transport Field Studies and Broad Test Plan

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The Vadose Zone Transport Field Studies (VZTFS) is an integral part of the Science and Technology Initiative of the Hanford Groundwater/Vadose Zone Project funded by the U.S. Department of Energy (DOE). The purpose of the VZTFS is to obtain flow and transport data for developing conceptual models and calibrating numerical models needed to improve predictions of contaminant plume migration in the vadose zone at the DOE Hanford Site near Richland, Washington. The study proposes a number of field experiments at Hanford over the next four years involving vadose-zone tracer tests at several uncontaminated sites. Identification of plume migration using advanced characterization tools will be part of the planned testing. This workshop will be used to help evaluate a suite of available technologies that can be used at Hanford to carry out the planned transport experiments in a cost effective manner. Further details of the broad test plan can be found as an attachment to these abstracts and also on the web at the URL address: <http://etd.pnl.gov:2080/vadose/>

Review of Geophysical Characterization Methods Used at the Hanford Site

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Geophysical methods have been used for characterization of hydrogeologic conditions and/or contaminant distributions at the Hanford Site since at least the mid- to late-1940s. A review of these geophysical methods is presented in two parts: 1) shallow surface-based geophysical methods, and 2) borehole geophysical-logging methods. Virtually all types of surface-based geophysical methods have been tested; including ground penetrating radar (GPR), numerous electromagnetic methods, magnetics, seismic, and gravity methods. To date, over 240 geophysical surveys have been conducted in portions of every "Area" of the Hanford Site. The most widely used geophysical methods are GPR, frequency domain electromagnetics (i.e. EM-31) and metal detectors. The geologic formations that make up the vadose zone are unconsolidated; thus, virtually every borehole is cased with schedule 40 steel pipe. The casing, and in later years a grout annular seal, have been the biggest factors in determining the types of logging methods used. Traditionally, gross gamma ray and neutron moisture probes were the two most commonly used downhole tools. Recently, spectral gamma-ray logging has replaced gross gamma-ray logging for most applications. Many other techniques (including prompt fission neutron logging and neutron-gamma logging for specific elemental analyses) have been tested and/or used for contaminant and lithologic characterization in the subsurface.

Review of Hydraulic Properties for Sediments in the 200 Areas

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Data on particle-size distribution, moisture retention, and saturated hydraulic conductivity (K_s) are cataloged for 183 samples from 12 locations in 200 Areas. The moisture retention data and K_s values are corrected for gravel content. After the data are corrected and cataloged, hydraulic parameters are determined by fitting the van Genuchten soil-moisture

retention model to the data. The database comprised of six soil categories and 176 samples is used as the basis for describing the probability distribution for the van Genuchten parameters and K_s. A scaling technique for similar media having linearly variable hydraulic properties is applied to simplify the description of the spatial variability. Results suggest that, for the soil types being considered, scaling can be successfully used to describe the variability of soil hydraulic properties.

Review of the Sisson and Lu Experiment

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Following a tank leak the horizontal and vertical extent of the plume depends on the permeability contrast of the sediment layers as well as their spatial distributions. In order to better quantify the permeabilities of the layer sediment found at the 200 East Area at Hanford a field experiment was done. The experiment consisted of injecting pulse of water a single point below land surface while measuring the water contents in 32 surrounding monitoring wells. The injected water contained the tracers ^{85}Sr, ^{134}Cs, Ca, Rb, Ba, NO_3^- and Cl and the concentrations of unstable isotopes were monitored in situ using gamma spectroscopy. Following the injection phase soil samples were obtained and analyzed for the tracers. The rate of plume spread was found to be controlled by relatively thin layers of silts and fine texture sediments. The data obtained were initially used to calibrate a 2D finite element code used in tank leak investigations. Subsequently the data have been used to evaluate additional models. Several problems that have been encountered in the modeling efforts that include a lack of in situ unsaturated hydraulic properties and the absence of soil water potential observations.

Tracer Technologies for Field Testing

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Tracers are an effective way of discerning flow and transport processes in porous media. Tracer tests are essential to understanding the vadose zone at Hanford because of the heterogeneities in soil properties and the chemical characteristics of fluid that have been introduced. Issues to be addressed are tracers, tracer application, sampling, and special conditions at Hanford. Desirable tracer characteristics for field testing will be presented. Initial emphasis will be on soluble tracers to examine flow and transport behavior for reactive and nonreactive species in aqueous solutions. Approaches and consideration of tracer application are important for analysis and interpretation of the data. Tracer sampling techniques are reviewed for the Hanford vadose zone field tests. Results from selected tracer studies are presented. Discussions of field tests with high ionic strength solution and colloid transport are needed for future planning.

Isotopic tracers for quantifying chemical processes during transport.

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One of the major uncertainties in simulations of chemical transport in hydrological systems is the kinetics of reactions. These uncertainties take several forms. For ion exchange, the rates of exchange are expected to be fast, but the available surface area for exchange is difficult to quantify. For chemical reactions, both reversible and irreversible, the available surface area for reaction is one uncertain parameter, but there are questions about whether the appropriate reaction mechanism can be specified, and about the rates when the system is close to equilibrium. Reaction rates measured in the field are often many orders of magnitude different from what would be predicted from laboratory experiments. Carefully designed experiments using isotopic tracers can often yield rates for key reactions (e.g. precipitation or dissolution of carbonate or silicate minerals, and volatilization). Examples are available for several isotope systems. Experimental results can also be used to calibrate the isotope systems so that past processes observed during characterization of contaminated sites can be interpreted.

Field Scale Dye Tracer Experiments: A Method for Delineating Vadose Zone Flow Processes

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Identification of site-specific vadose zone flow processes is fundamental to understanding transport mechanisms responsible for observed contaminant distributions, assessing the extent of contamination beyond sampled areas, and predicting the fate of the contaminants. Among the methods available for studying vadose zone flow processes, dye tracer studies stand out as one of the best methods for identifying flow and transport pathways by providing direct visual evidence. We have performed dye tracer studies in a variety of geologic materials ranging from a glacial till comprised of fractured clay deposits, fractured tuffs, and sandy fluvial deposits. Results from these studies have provided critical insight required for the proper conceptualization of flow processes in each of these environments. Structural interfaces affect the fingered flow paths by creating capillary fringes when a fine layer overlies the coarse-grained layer but in most cases will enhance preferential transport. Sampling will be most effective in the capillary fringes above the structural interfaces. The reason is that the velocity of the flow is slower in theses regions and there is less chance of bypassing the samplers. In experiments on Long Island and Freeville, NY (both with sandy profiles) we found that suction cup samplers in these regions gave a more realistic pattern of leaching than cup samplers in other parts of the profile. Another sampling technique that gave good results was the wick sampler. Its placement is not dependent on the availability of structural interfaces. In sandy soils, pan samplers without wicks perform poorly due to bypassing of the samplers. In all cases, the addition FD&C blue dye #1 (with des) helped in understanding the flow pattern that led to the observed concentrations.

Field Tracer Tests to Characterize the Vadose Zone Geochemical and Hydrologic Properties

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At the Hanford Site, interpreting existing contaminant plumes and predicting the fate and transport during future contamination characterization and remediation efforts will require knowledge of the in situ hydrologic properties, as well as the magnitude and characteristic length scales of the variations in those properties. Current monitoring technologies are mostly invasive and provide only local scale, near-surface measurements, thus limiting our ability to determine spatial-scale dependence and to establish relationships between hydraulic properties and observed flow and transport phenomena, especially at the field-scale. In the recent past, innovative tracer methods were developed to measure various hydrologic properties at both field and laboratory scales. We report here on the development of tracer-based methods for an integrated, noninvasive characterization of the vadose zone. The critical hydrologic and geochemical characteristics necessary for the Hanford Site vadose zone characterization are water saturation (S_w), air saturation (S_a), hydraulic conductivity (K), relative permeability ($k_{r,i}$), air-water interfacial area (a_{aw}), air morphology index ($I = S_a/a_{aw}$) to characterize the morphology of air, water morphology index ($I = S_w/a_{aw}$), Effective Diffusion coefficient (D_e), Tortuosity factor (τ), Constrictivity factor (δ) and Dispersion parameter (D). Using non-reactive, interfacial, partitioning and geochemical tracers in tandem, many of the above hydrologic and geochemical parameters and their scale-dependent variability can be measured in field-scale characterization experiments. At the Hanford Site, where the water saturations are very low, gas phase partitioning and interfacial tracers are particularly valuable for such characterization. Tracers injected through the aqueous and/or gaseous phases of the vadose zone and recovered through multi-level samplers (MLS) and extraction wells in a controlled field tracer experiment yield valuable data toward such characterization. We will present the theory, methods and some recent results from tracer tests, and a plan for field tracer testing for vadose zone characterization.

Advanced Characterization and Monitoring of Chemical Transport in the Vadose Zone at Hanford

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The presentation will include the discussion of: (1) the problem of uncertainty of measurements of water travel time and chemical concentration in the vadose zone using the results of three-dimensional numerical modeling of flow in spatially heterogeneous soils, (2) the results of the ponded infiltration and tracer tests in fractured rocks, (3) the design and application of several innovative field methods for soil liquid sampling and monitoring, including advanced suction lysimeter, miniature electrical resistivity probes, water- and concentration-flux-meters, and soil gas monitoring (radon concentration and air permeability) to locate zones of potential preferential flow.

In Situ, Real-Time Characterization of Soil Processes with Fiber-Optic Mini-Probes

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Many of the characterization studies of solute transport in the vadose zone require nondestructive measurement of water flow and solute transport parameters at temporal and spatial resolutions far beyond the capabilities of our existing methodologies. Using remote fiber optic fluorometry (RFF) techniques we have developed a 20-channel fiber optic mini-probe (FOMP) system, which allows in situ measurement of solute transport processes in soil in real time and on a continuous basis. The system consists of transmitting a constant beam of light through the input leg of a bifurcated fiber optic mini-probe to a location of interest within the soil matrix. At the probe's tip, the incoming light interacts with the soil matrix where it is partially absorbed and partially reflected back into the probe. The reflected signal is transmitted through the output leg to a photo-detector and quantified. The intensity of the output signal, which is constant under steady conditions, changes when the optical properties of the soil matrix in front of the probe change, allowing for measurement of water content and solute breakthrough curve at the "point" of observation. The development of our multiplexed FOMP system and its application to the measurement of water, particle, and solute transport processes in both laboratory and field soils will be discussed.

Core and Outcrop-scale Permeability Mapping Using IR Imaging

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Ultrasensitve Infrared (IR) imaging can be used to develop detailed permeability maps of meter scale outcrops or split cores revealing heterogeneity at scales ranging from 1 m to a few mm. To date this has been achieved by empirical comparison of air permeability measurements with IR intensity using images produced by a cooled CCD imager (256x256 pixels) capable of distinguishing pixel to pixel temperature differences of 0.025 degrees Celsius. The resulting digital image thus records minute differences in temperature on a newly exposed or newly wetted face containing the sediments or other geological features of interest. These temperature differences are related to permeability by the relative moisture retention with low permeability zones exhibiting lower temperatures because of evaporative cooling of retained moisture. Higher permeability zones lose moisture and evaporative cooling is insufficient to maintain cool temperatures under incident sunlight. Using air permeability measurements, these temperature differences can be correlated to permeability and the image transformed to a permeability map. Applied to sandy sediments, this method has yielded the first 2-D permeability map of an area 1mx2m with spatial resolution less than 1 cm. This approach is currently being applied to cores from a bacterial transport site in a sandy aquifer in coastal Virginia, and will soon be applied to clastic dikes at the Hanford Site. However, it has not been applied to cores from the vadose zone at Hanford, nor has the IR imaging been adapted to produce unsaturated permeability parameters. IR imaging of cores from the Vadose Zone Test Facility is recommended to provide detailed information on saturated permeability as an indicator of heterogeneity. Further development of the technique may permit extraction of unsaturated permeability parameters.

Monitoring and Characterization Equipment Development at INEEL

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Three boreholes at the Savannah River site have been instrumented at several elevations with Advanced Tensiometers, Borehole Water Content Sensors, and vacuum lysimeters to total depths of 15 m. These sensors achieved equilibrium conditions within 60 days and record water potentials to within 5 cm, and water content to within 0.0002 m(superscript: 3) m (superscript: -3). Historically, sensors available for this purpose have been limited to shallow systems, and limited by reliability and range of detection. However, these new instruments and installation techniques allow detection of barometric pressure fluctuations that are observed in water potential and water content data. This paper will present the instrument designs, the Savannah River data, and discuss potential uses of these instruments at the Hanford site.

Unsaturated Hydraulic Properties of Uncontaminated WMA S-SX Vadose Zone Sediments

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A state-of-the-science technique will be developed to obtain parameters that can be used to accurately describe unsaturated hydraulic properties in the vadose zone. Measurements will be conducted on core samples from key subsurface strata at the Hanford 200 West Area that strongly impact subsurface flow and transport behavior. The resulting data will provide a baseline from which measurements on contaminated cores can be compared to assess changes in hydrologic properties due to the leakage of high salinity/caustic waste solutions from the S-SX Tank Farms. In addition, parameters determined from the measurements will be compared to parameters from other measurement techniques to assess benefits of using the various methods and to recommend a common measurement system for unsaturated hydraulic properties at the Hanford Site. The work will be integrated with activities in the Vadose Zone Transport Field Study of the Groundwater/Vadose Zone Integration Project. The state-of-the-science technique will consist of transient and steady-state measurements. Methodology will be similar to multistep outflow measurements, except a flux boundary condition will be employed in a stepwise manner so that unsaturated permeabilities can be directly measured. During transient flow conditions, water contents will be measured using time-domain reflectometry and water pressures will be measured using transducers. In addition, water outflow measurements will be conducted. At steady-state conditions, unsaturated permeabilities, water contents, and water pressures will be measured. A numerical algorithm will be used to determine hydraulic properties based on the transient measurements. However, the solution to the problem will be restrained by the steady-state measurements. This approach will yield more accurate parameters relative to single or multistep outflow methods, which is important for developing a subsurface physical model from which flow and transport simulations will be conducted.

Viability of Rapid *in situ* Measurement of Hydraulic Properties

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The spatial variability of unsaturated hydraulic properties in heterogeneous geologic materials directly influences the movement of water and non-aqueous phase liquids (NAPL's) through the vadose zone. One approach to characterization requires a large number of hydraulic property observations, which would then be interpreted using geostatistical or geological models. Removing multiple samples for laboratory analysis is expensive, time-consuming, and may not yield results representative of heterogeneous field conditions. Simple and rapid field methods for estimating *in situ* properties are appealing and potentially cost-effective. We discuss the viability of methods for the direct measurement of saturated and unsaturated hydraulic conductivity on outcrops and in excavations. With these methods 1) measurements should be relatively rapid, 2) the total cost per data point should be low, 3) results should accurately reflect the variation of unsaturated hydraulic properties between sampled locations, 4) the volume sampled (measurement support) should be small, and 5) the instrument range should be relevant to the range of conditions typically encountered in clastic sediments with low clay content (such as found at many DOE sites).

Uncertainty and Upscaling of Vadose Zone Flow and Transport at Hanford

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An EMSP research project intimately related to the Science and Technology Initiative on VZ Transport will focus on the development of a general approach for modeling flow and transport in a heterogeneous vadose zone. The approach will use geostatistical analysis, media scaling, and conditional simulation to estimate soil hydraulic parameters at un-sampled locations from field-measured water content data and a set of scale-mean hydraulic parameters. Results will help to elucidate relationships between the quantity and spatial extent of this characterization data and the accuracy and uncertainty of flow and transport predictions. An example of media scaling and simulations conditioned on initial water content profiles will be presented for the Sisson and Lu Site at Hanford. Some on the discussion will focus on neural network pedotransfer functions and conditioning data on both core samples and geophysical measurements. We will also discuss the effectiveness of an upscaling approach where unsaturated hydraulic properties are obtained from a limited number of small (<200 g) samples whose characteristics have been determined by conventional laboratory techniques and used to estimate the shape and spread of the water plume in the subsurface

Application of Geophysical Methods for Characterization and Monitoring of Properties
Controlling Flow and Transport in the Vadose Zone at the Hanford Site.

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Over the last fifteen years LBNL has been developing and applying high resolution geophysical methods for characterizing and monitoring contaminated subsurface environments. This has involved field studies at a variety of DOE contaminated sites (SNL, SRL, ORNL, BNL, DOVER, LLNL, LBNL, Hanford, etc.) in both the vadose and saturated zones. The focus has been on developing geophysical techniques and interpretations that provide information on properties controlling flow and transport, rather than presenting the results in traditional geophysical parameters. For example, developing the relationship between moisture content and radar response, then providing an image of moisture content and permeability rather than dielectric constant. In this work we have found that such issues as scale of heterogeneity, variation of heterogeneity, lab to field scaling, and laboratory validation are critical to a successful understanding of the relationship between the geophysical data and flow and transport properties. In all of our work the most important lesson has been that each site is distinct and there is no universal method of choice. In almost all cases in order to obtain the necessary resolution and understanding of the critical properties controlling flow and transport (especially in fast path environments) multiple methods must be used in a complimentary fashion at multiple scales. Presented will be examples of high resolution geophysical studies (both seismic and radar) and how the results may impact the vadose zone studies at Hanford. Also presented will be results of recent (Jan 10 - 13, 2000) radar and magnetotelluric work carried out by LBNL/PNNL at Hanford and implications for characterization and monitoring of the proposed infiltration tests.

Performing Vadose Zone Experiments and Interpreting Hydrologic Observations at Hanford

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The EMSP-supported LLNL Vadose Zone Observatory (VZO) is a highly instrumented facility that was developed to elucidate processes associated with the transport of contaminants across the vadose zone from the near-surface to the water table. Infiltration experiments carried out at the VZO usually involve the creation of a plume that is tracked both by tomographic methods such as electric resistance tomography (ERT) and by more standard hydrologic techniques involving tracers, lysimetry, tensiometry, temperature and gas-phase pressure changes. To date, the role of modeling has been to provide a framework for interpreting the results of the various observations and as a method to evaluate the relationship between laboratory measurements, geologic observations, and the data obtained in field experiments. Lessons learned during this experience have many potential benefits to the establishment and operation of a field research facility at Hanford. For example, we find that information such as tomographic images of infiltration events may not be readily interpretable in the absence of some effort in advance to relate these snapshots to the hydrologic processes responsible for them. In addition, it was shown that multiple methods should be employed wherever possible to yield observations which can be combined to reduce the non-uniqueness of a given parameter distribution such as formation permeability or soil moisture. The implications of these conclusions for planned Hanford experiments, cost-effective leveraging through the use of existing facilities and possible roles for modeling as suggested by our experience at LLNL will be discussed.

Effects of Fluid Distribution on Measured Geophysical Properties for Partially Saturated, Shallow Subsurface Conditions.

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Geophysical techniques provide a relatively non-invasive and cost-effective alternative to drilling, for subsurface characterization and restoration monitoring at contaminated sites. Various geophysical methods can provide information at a variety of scales, for 3-dimensional regions that are not sampled by drilling. Seismic imaging methods in particular are useful because modern field techniques allow the collection of two independent types of seismic data (compressional and shear wave data), these data are sensitive to fluid content, and seismic methods are not adversely affected by metal-cased boreholes. In order to improve the state-of-the-art for shallow seismic imaging, this new EMSP project focuses on improving the interpretation of seismic field data by conducting laboratory ultrasonic velocity measurements under controlled conditions and by developing the rock physics theories relating measured seismic parameters to hydrogeologic properties such as porosity and saturation. This work is a continuation of work begun in an earlier EMSP project, but the emphasis now is on seismic data and vadose zone conditions (i.e., partial saturation). We are also using x-ray computed tomography to image the microstructure of the samples, to help develop a better understanding of how microstructure controls measured properties. We will make laboratory measurements on well-understood materials such as Ottawa sand and Lincoln sand, and also measure properties of Hanford sediments when such samples are available. Results from this EMSP project will not only provide a database of these measured properties, but will also provide appropriate recommendations for seismic field experiment design at Hanford, recommendations for use of various sonic/seismic techniques, and some guidelines for field data interpretation.

Use of Radar Methods to Determine Moisture Content in the Vadose Zone

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Surface and borehole radar methods have the potential to provide high-resolution, non-invasive images of the dielectric properties of the subsurface, that can be used to map out spatial and temporal variation in moisture content. There are two ways that radar data can be used to obtain information about moisture content: 1) invert the radar data to obtain a model of the subsurface in terms of the dielectric constant K' of regions of the subsurface; transform the model of K' to a model of water content, using the appropriate relationship between K' and water content; 2) use the radar image directly to estimate the spatial variability in moisture content by quantifying the heterogeneity seen in the radar image. With either approach, there are some important research questions, which are the focus of our ongoing research project. Our progress to date in some of these issues will be discussed, as briefly summarized below. A critical step in taking the first approach is obtaining the dielectric model of the subsurface. We have recently completed a study where we have used cone penetrometer data to improve our ability to obtain an accurate model of the subsurface from surface seismic data. We plan to test the same methodology by combining surface radar data with "subsurface" (borehole, cone?) radar data. In the first approach, once a dielectric model is obtained, the accuracy of the water content determination depends upon the relationship used between the dielectric measurements and water content. We have begun the development of an inversion algorithm that can incorporate uncertainty about spatial heterogeneity to better constrain the uncertainty in the estimates of moisture content. In the second approach, we use a geostatistical analysis of the radar image to quantify the observed spatial heterogeneity. Recent work with multi-frequency radar data has shown a scale-dependence in the results related to the resolution of the radar image. Regardless of whether the approach is 1) to develop a dielectric model or 2) to describe the variability in the radar image, the first required step is an improvement in the clarity of the radar image itself. Our first task has been to find an optimal way to correct for frequency-dependent attenuation; this is responsible for wavelet dispersion, which is displayed in the radar image as a characteristic "blurriness" that increases with depth. We have estimated the amount of wavelet dispersion in GPR data using wavelet transform "frequency spectra". These estimates can then be used to correct for frequency-dependent attenuation using an inverse Q filtering technique.

Cross hole radar tomography in an alluvial gravel deposit

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Crosshole radar tomography is used increasingly to characterize the shallow subsurface and to monitor hydrologic processes. At the Boise Hydrogeophysical Research Site (BHRS), we are characterizing the hydrogeophysical parameters of a cobble-and-sand, unconfined aquifer using crosshole radar tomography. Our goal is to develop methods for mapping variations in permeability by combining non-invasive geophysical data with hydrologic measurements. We have analyzed crosshole radar data acquired between closely spaced wells with a finite-difference eikonal equation based tomographic inversion method to provide estimates of velocity and structure between wells. Supporting data sets from the BHRS include core analyses and geophysical logs from 18 wells at the site. We will use these data to verify our geophysical interpretations. The radar velocities estimated from the tomographic inversion correlate with porosity logs derived from neutron borehole geophysical tools at the BHRS. The crosshole radar method, combined with the well control, will provide an outstanding data set to characterize the heterogeneity of the subsurface beneath this alluvial aquifer and will find ways to map permeability with geophysical information.

Hydraulic/Pneumatic Tomography: A Site Characterization Method

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Hydraulic/pneumatic tomography has recently been proposed as a method for characterizing aquifer and vadose zone heterogeneity. During a hydraulic/pneumatic tomography experiment, water or air is sequentially pumped from or injected into an aquifer or vadose zone at different vertical portions or intervals of the geological medium. During each pumping or injection, hydraulic head responses of the medium at other intervals are monitored, yielding a set of head/discharge (or recharge) data. By sequentially pumping (or injecting) water (or air) at one interval and monitoring the steady-state head responses at others, many head/discharge (recharge) data sets are obtained. An inverse approach to interpret results of the hydraulic/pneumatic tomography experiment is developed. For each set of hydraulic tomography data, an iterative geostatistical inverse approach is employed to determine the effective hydraulic conductivity field of the medium, conditioned on the available head and conductivity measurements. To avoid numerical difficulties associated with simultaneous inclusion of all the head data sets, a sequential conditioning approach is developed. The method was applied to hypothetical, two-dimensional, heterogeneous aquifers to investigate the optimal sampling scheme for the hydraulic tomography, i.e., the design of well spacing, pumping and monitoring locations. The effects of measurement errors and uncertainties in statistical parameters required by the inverse model were also investigated. The robustness of this inverse approach was then demonstrated through its application to a hypothetical, three-dimensional, heterogeneous aquifer. A laboratory sandbox experiment was also conducted to illustrate the validity of the approach. Finally, we believe that combining with our inverse approach, the hydraulic/pneumatic tomography can be a powerful and cost-effective technology to delineate aquifer and the vadose zone heterogeneity.

Microhole Drilling and Instrumentation Technology

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Los Alamos, supported by the DOE in collaboration with the oil industry, has undertaken an integrated program directed toward drastically reducing the scale and cost of drilling that has as its intended purpose subsurface measurement. Termed “Microhole Drilling and Instrumentation Development,” these engineering efforts encompass: miniaturization and testing of bottomhole coiled-tubing drilling assemblies, automation of drilling controls, miniaturization of geophysical logging tools, and incorporation of emerging sensor technologies in borehole instrumentation packages. Microhole technology development is based on the premise that conventional-diameter wells, which are optimal for the production of fluids, are no longer either necessary or the least expensive method for obtaining subsurface information. Currently, Los Alamos is drilling and casing 2-3/8-inch-diameter microholes to depths of 500 ft with an experimental coiled-tubing drilling platform using a mud system. The drilling to date has been in basin-and-range valley fill and volcanic tuff. The development of microhole technology directed specifically to environmental applications would have much to offer. Microhole coiled-tubing drilling at the 1-3/8-inch diameter: produces less than two barrels of cuttings per 1000 ft of drilling, contains and re-circulates drilling fluids, has an inherently small drill site, and offers the prospect of low-intensity capital development projects to rapidly advance special-application supporting technologies. While Los Alamos has demonstrated the essential and supporting technology elements of a microhole drilling system, work to date has only advanced to the stage of using mud systems for drilling 2-3/8-inch-diameter microholes. For vadose zone applications, an air microhole drilling system is necessary. Los Alamos experience in testing air-driven positive displacement motors (PDMs) and bits under laboratory conditions suggests that a coiled-tubing drilling bottomhole assembly combining a PDM and a percussion bit would enable efficient microhole drilling with air.

Estimation of Soil Hydraulic Properties with the Cone Permeameter

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Field application of the cone permeameter method for estimating the soil hydraulic properties: the soil-moisture characteristic curve, $\theta(h)$, and hydraulic conductivity function, $K(h)$, is presented. The cone permeameter has been designed to inject water into the soil under known pressure while the cumulative inflow volume and pressure heads measured with tensiometer rings at two locations above the water source are recorded in time. The observed data sets are analyzed using an inverse modeling method to predict the soil hydraulic properties. The device was tested for the first time in the field in two types of sandy soil. Tests were always conducted with two sequentially applied pressure heads of different magnitudes for different experimental runs. After the water source was shut off, tensiometer measurements were continued to monitor the redistribution of water in the soil. To study the impact of one or two steps of applied pressure head on estimates of wetting soil hydraulic properties, we carried out numerical inversions for data from the injection (wetting) part of experiment first with only one supply pressure head, and then with two supply pressure heads. For selected tests we analyzed data from the entire experiment to investigate hysteresis of the soil hydraulic properties. The resulting soil hydraulic properties correspond well with those obtained with standard techniques.

CPT Vadose Zone Characterization and Monitoring Tools.

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Cone Penetrometer Techniques have been used over the past ten years at the Hanford Site. A summary of the depths achieved along with push requirements are presented. During the penetrations a variety of sensor systems have been deployed and the basics of the sensors will be described and the results obtained presented. The sensors range from gamma spectroscopy tools to soil moisture and hydraulic conductivity sensors. The presentation will be summarized by discussing applications of CPT.

Direct-Push Spectroscopic and Imaging-Based Sensor Systems for Characterization of Vadose Zone Hydrologic Conditions and Contaminant Distributions.

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The distribution and transport of subsurface contaminants may often controlled by small-scale variations in subsurface soil properties. Variations, such as the presence of a thin layer of low permeability material, may be difficult to delineate with traditional soil sampling methods or other non-invasive techniques. Without detailed knowledge of subsurface soil characteristics, it is unlikely that transport models will accurately predict the fate of subsurface chemical contaminants. In this presentation several new direct push sensor systems will be described that extend the capabilities of penetrometer based sensor systems. These new optical based sensors build on the approach that was first used for in situ measurement of petroleum hydrocarbons via laser-induced fluorescence (LIF). One new sensor system makes use of Laser-Induced Breakdown Spectroscopy (LIBS) for real-time in situ measurement of metals in soils. This sensor uses a high powered pulsed laser coupled to an optical fiber in order to generate a plasma on the surface of the soil in contact with a sapphire window installed on the probe. Atomic emission signals from metals on the soil is transmitted back to the surface and quantified with a linear photodiode array. Results from several field demonstrations will be presented and compared with traditional laboratory methods. In addition, an in situ video imaging system will be described that consists of a miniature CCD color camera and associated optics and illumination system that provides a capability for real-time, high-resolution imaging of subsurface soil characteristics. Examples will be given for the use of the in situ imaging system for documenting small-scale variability in lithology based on differences in soil color and soil texture. Data will also be presented that shows the capability of the camera system for delineating zones of free-phase Non-Aqueous Phase Liquid (NAPL) (e.g., TCE (tri-chloroethylene) in the subsurface.

Development of a Miniaturized *in situ* X-ray Diffraction/X-ray Fluorescence Instrument for Vadose Zone Characterization.

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We have developed a miniaturized instrument that performs both X-ray diffraction and X-ray fluorescence measurements on powdered samples of sub-milligram size. This instrument employs transmission geometry and a charge-coupled device (CCD) detector. Use of the CCD detector in single-photon counting mode allows simultaneous determination of both spatial (diffraction) and photon energy (fluorescence) information. Energy discrimination, made possible by the use of single-photon counting methods, is used to distinguish between diffracted characteristic photons and fluorescence photons. Diffraction events impinging on the two-dimensional CCD detector yield rings that can be circumferentially integrated to produce a conventional X-ray diffraction pattern. Qualitative X-ray fluorescence data are presently obtained by analyzing the charge deposited in each of the 512X512 pixels. At present, a standard laboratory X-ray tube is used, but the future instrument will use a miniaturized X-ray source of new design, presently being developed under an active phase-II DOE Small Business Innovative Research grant. Our instrument, a recipient of a 1999 R&D100 Award, was originally conceived to provide mineralogic data from extraterrestrial bodies such as Mars. The projected flight-instrument weight is ~1 kg, volume 500 cc, and power requirement is ~1 W. Usable diffraction data have been obtained from the prototype instrument in our laboratory in a few minutes, and flight-instrument data-collection times of 1-2 hours are predicted. We propose significant modification of the existing flight-instrument design to allow its use for *in situ* analysis in remote terrestrial environments. These modifications will allow use of the instrument with solid, unpowdered samples and should permit measurement of diffraction data in remote, field, or down-hole environments.

An Integrated Approach for Characterizing and Monitoring the Vadose Zone and Aquifer.

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Knowledge of the spatial distribution of hydraulic properties, water, and contaminants in the vadose zone and aquifer is important to our management of water resources. It is therefore imperative to have a cost-effective methodology that can identify the spatial distribution of hydraulic properties and monitor the movement of water or contaminants in the vadose zone and aquifer. In this study a cost-effective/integrated characterization/monitoring methodology is developed, which takes advantage of the ability of electrical resistivity tomography (ERT) for monitoring changes in water content or concentration over a large volume of geological media. It then integrates the resistivity measurements with sparse point measurements of hydraulic properties, moisture content, concentration, and pressure to simultaneously identify the spatial distribution of hydraulic properties and water or contaminants in the vadose zone and aquifer. The cost-effectiveness of the method stems from the fact that the method can produce maps of subsurface heterogeneity or water and contaminant plumes at high resolutions with the minimum number of destructive samples. The data interpretation procedure of our approach uses a new hydrological/geophysical joint inversion concept. Existing concepts have concentrated only on the use of geophysical tools for characterizing the subsurface to enhance hydrological modeling. Our joint inversion, however, recognizes that hydrological information provides useful constraints for the ERT interpretation and meanwhile the ERT can furnish a vast amount of water content and concentration information for hydrological inverse modeling. Because of the reciprocal nature of the hydrological and geophysical information and inversions, our joint inversion takes an iterative approach until given hydrological and geophysical information is fully utilized. Finally, our approach allows us to simultaneously characterize heterogeneities and monitor distributions of moisture or tracers in both unsaturated and saturated zones in an integrated manner. The approach produces approximate conditional mean and variances of parameters, pressure head, moisture content, concentration, and resistivity fields. Thus, uncertainties associated with our characterization and monitoring can be addressed.

Application of Oilfield Drilling and Borehole Geophysical Technologies to Vadose Zone Characterization

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The oilfield service industry provides access to exploration and production technologies that may be applied to vadose zone characterization. Specific technologies of interest include coiled-tubing drilling with low-invasion drilling fluids and logging services applied in steel-cased boreholes. Coiled tubing is a continuous length of pipe wound on a spool as drill string. The pipe is straightened prior to pushing into a wellbore and recoiled to spool the pipe back onto the transport and storage spool. Coiled tubing can be used with downhole mud motors to drill a wellbore. Coiled tubing drilling operations proceed quickly compared to conventional rigs because connection time is eliminated during tripping, and the coiled tubing rig can be set up in a matter of minutes. Most coiled tubing drilling is directional where a bottom hole assembly is used to deviate the wellbore. Downhole instruments continuously monitor the wellbore path in thee-dimensional space to permit the drilling of a pre-defined trajectory. Horizontal well paths of many hundreds of feet are commonly drilled. The downhole mud motor can be driven by compressed gas or drilling fluids (i.e., drilling mud). In addition to turning the bit, drilling fluids stabilize the wellbore, transport drill cuttings to the surface, and lubricate. Drilling fluids would be necessary to drill horizontal wells in unconsolidated formations to stabilize the wellbore. Advanced fluids with a high degree of low-shear-rate viscosity (LSRV) would be recommended to control leakoff. As the LSRV begins to leak off to the formation, the shear rate to which it is exposed decreases, causing the LSRV to form a viscous filtrate that will not significantly penetrate the formation and control further invasion. Borehole logging systems can be used in new and existing steel-cased boreholes to provide key characterization vadose zone properties including: porosity, moisture content, lithology / mineralogy, gamma-emitting contaminant activity, other hazard and rad contaminant concentrations, pore water salinity, the extraction of pore waters and casing condition. The majority of these measurements are made with mature, commercial technologies. Several were demonstrated successfully for vadose zone characterization at the Hanford site as a CRADA. An emerging logging technology is the measurement of formation electrical resistivity from a steel-cased borehole. This measurement is a formidable task because of significant contrast between electromagnetic properties of casing and formation. It requires stationary measurement at two points 2 ft apart simultaneously, and each measurement takes 2 minutes. The use of multiple electrodes leads to an equivalent logging speed of 120 ft/hr. Vertical resolution is 4 ft and depth of investigation is approximately 6 ft.

Electrical Resistance Tomography- 4D Underground Imaging.

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Underground imaging using galvanic currents has been developed over the past 10 years at Lawrence Livermore National Laboratory for a variety of environmental uses. Recently it has been used for 3 dimensional imaging as a function of time (4D) to monitor various soil and ground water remediation. These include steam floods, air sparging, vacuum extraction, radio frequency heating and ohmic heating. The method has also been used to map the moisture distribution in rock and soil. Fore example, at the 200 E Area at Hanford we monitored a salt-water release from a mock tank in an effort to determine if electrical resistance tomography (ERT) could be used to detect leaks from single shell tanks. In that test the method provided detailed images of changes in moisture content as the water plume developed over a period of several days. In this presentation, we provide a brief overview of ERT describing requirements for electrode arrays; r elation between sensitivity, resolution and data coverage; working at a site with steel casing; comparison with other geophysical data; general strengths of the method; and limitations of the method. We also offer suggestions on the use of ERT at the proposed Hanford Vadose Zone Test Site Facility with some guidelines on realistic expectations.

High Resolution Resistivity: Applications and Case Histories

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Detecting and mapping moisture distribution in the vadose zone is a logical application of electrical and electromagnetic geophysical methods. The presence or absence of moisture directly affects the distribution of the subsurface electrical field. Electrical and electromagnetic resistivity surveys have been successfully performed on a wide variety of environmental projects. Geophysical methods can be applied from simple one-dimensional soundings to time-dependent three-dimensional arrays (4-D). The general drawbacks to the more widespread use of geophysical methods have been poor resolution, lack of continuity between soundings or traverses, poor repeatability, high cost, and, unfortunately, a poor understanding of the basic physics of the methods. The high resolution resistivity (HRR) method offers a solution to these drawbacks of the past.

Several HRR case histories will be presented. These examples graphically show how HRR has improved data resolution, continuity, and repeatability while dramatically lowering the cost of surveys.

Crosswell Electromagnetic Imaging for Characterizing Saturation Changes within the Vadose Zone

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Measurements of cross-well electromagnetic fields provide a means of mapping electrical conductivity variations between boreholes and the associated changes in subsurface saturation. Hence the method has important applications for mapping potential pathways for contaminant transport if such pathways are associated with increased saturation in the vadose zone. The method can also be used for monitoring saturation changes over time thereby mapping new zones of increased saturation, which could be a possible conduit of further contaminant transport. The review article of Wilt et al., 1999, describes the instrumentation and field procedures for making cross-well measurements. In processing of cross-well data, the inversion process is essential in producing a map of conductivity changes within the inter-well region, associated with saturation changes in the subsurface. In this talk we will present theory and case histories of the method. Field examples to be presented include characterizing transport pathways of contaminants and mapping saturation changes in oil reservoirs over time due to water flooding. Finally, measurements through steel casing will be discussed, since many boreholes are steel cased at environmental waste sites, such as at the Hanford reservation. Recent advances have demonstrated that cross well electromagnetic measurements through steel casing are possible, provided the inter-well region is sufficiently conductive, greater than 0.1 S/m. Such measurements have been demonstrated at well separations up to 300 meters and numerical studies indicate the probability of extending this range to the order of 1km.

Three-Dimensional P and S Wave Seismic Imaging of Shallow Structures.

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We will describe our recent research efforts in shallow seismic subsurface imaging at the Center for Imaging the Earth's Interior (CIEI) and at GEOTOMO, an Industrial Affiliate of CIEI. Our work is dedicated to developing and applying 3D compressional (P) and shear (S) wave imaging methodologies. We will present examples of existing capabilities in 3D P tomography and emerging capabilities in imaging shear velocity. New capabilities are based in part on interpreting interface or surface waves to infer shear velocities. We will discuss the relevance of these methods for vadose zone characterization and will attempt to describe the context in which seismic tomography may be used to complement and augment EM resistivity tomography and NMR imaging.

Magnetic Resonance Dowsing

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The general theory of surface NMR imaging of large electromagnetically active systems will be described and applied to noninvasive geophysical applications such as the imaging water content and pore size distributions in the first 100m or so of the subsurface. A general imaging equation is derived for the NMR voltage response, valid for arbitrary transmitter and receiver loop geometries and arbitrary conductivity structure of the sample. When the conductivity grows to the point where the EM skin depth is comparable to the sample size, significant diffusive retardation effects occur that strongly affect the signal. Accounting for these in the analysis of experimental data now allows more accurate imaging than previously possible. Future technological improvements needed for this technique to achieve its full potential will be discussed.

Field Experiments and Characterization for Reactive Radionuclide Transport

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Although it is expected that field experiments and site characterization at the Hanford site will initially focus on physical aspects of flow and transport, it is useful at this stage to discuss possible field experiments and characterization for future reactive radionuclide experiments. The field experiments and characterization of non-reactive flow and transport, especially characterization of fast pathways, will provide a baseline for assessing the effects of various chemical reactions on radionuclide mobilities, both for modeling purposes and if and when the reactive transport experiments are eventually carried out. A reactive radionuclide transport field experiment obviously requires additional geochemical characterization. Geochemical characterization data that is needed includes the distribution of primary and secondary reactive minerals (e.g., illite, smectite, feldspar, magnetite, and calcite), and their associated grain size (primarily for the purposes of surface area characterization). With further laboratory work, these data can be used to estimate the distribution of multiple sorption and ion exchange sites, although the characterization might include direct determinations of sorption also. In addition, it will also important to determine the correlation between various physical and chemical parameters (e.g., hydraulic conductivity and the distribution of cation exchange sites) in order to develop realistic models of radionuclide migration. One possible field experiment would involve the injection of a high pH electrolyte solution into the vadose zone. This injection could be accompanied by one or more non-radioactive isotopes of the relevant radionuclides at Hanford (e.g., cesium). A high pH and strong electrolyte e fluid is needed in order to attempt to replicate conditions observed under the leaking Hanford tanks (field temperatures would obviously not be a realistic representation of the tank environment). The high pH is expected to affect radionuclide sorption and the precipitation of secondary aluminum and aluminosilicate phases. It may also lead to significant changes in concentrations of other solutes (e.g., K^+), which could effectively complete with radionuclides for sorption sites. Characterization of the time scales for reactions, the hydrologically accessible reactive surface area of minerals, and effective exchange capacity of the in situ Hanford sediments would greatly aid modeling studies at the Hanford Site.

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